Tutorial on

Advanced Atomic Clocks

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IEEE Frequency Control Symposium

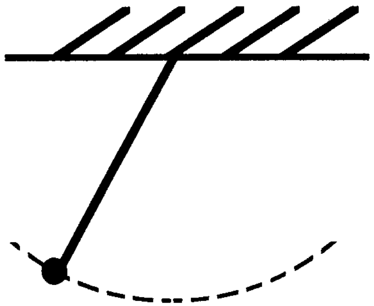
Introduction

- Christian Huygens' (Galileo's?) pendulum clock (1582) was stable to 1 min/day, but useless for moving platforms
- John Harrison's "Marine Chronometer" (1761) kept time on a rolling ship to .2 s/day; determined longitude to 0.5 deg
- Quartz clocks have evolved from 1930's to be stable to better than 1 part in 10^{13}
- Uncertainty in the location of S/C at Jupiter with quartz is 300 km
- DSN's capability better than 1 part in 10^{15}

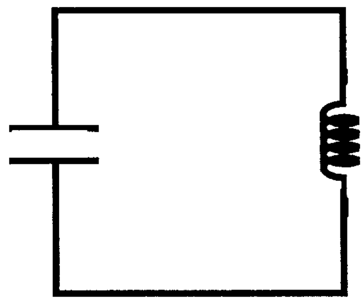
Outline

- Introduction
- Principle of operation of atomic clocks
- Need for laser cooled clocks
- Principles of laser cooling
- Laser cooled neutral clocks
- Laser cooled ion clocks
- Future -- Laser cooled clocks in space

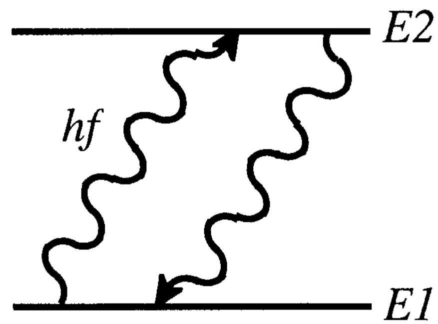
The Physical Oscillator



$$f = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$$



$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$



$$E_2 - E_1 = hf$$

For time and frequency standard applications we need oscillators that yield the same frequency at <u>all</u> <u>times</u> and <u>all</u> <u>places</u>!

DESIRED CHARACTERISTICS OF ATOMS FOR FREQUENCY STANDARDS APPLICATIONS

- SIMPLE ATOMIC LEVEL STRUCTURE SCHEME
- A TRANSITION INVOLVING TWO NARROW LEVELS, i.e. LONG LIFETIME
- TRANSITIONS WITH LARGE LINE Q, $Q_l = F_0/\Delta F$
- LEVELS WITH SMALL SENSITIVITY TO EXTERNAL PERTURBATIONS
- TRANSITIONS WITH "ACCESSIBLE" FREQUENCY : <u>MULTIPLY AND DIVIDE WITH EASE</u>

SOLUTION: USE HYPERFINE TRANSITIONS IN ALKALI ATOMS, AND ALKALI-LIKE IONS

Sources of Atomic Line Broadening

- FIRST ORDER DOPPLER EFFECT
- COLLISIONAL BROADENING; PRESSURE BROADENING
- ENVIRONMENTAL PERTURBATIONS (E AND B FIELDS)
- INTENSITY DEPENDENT SHIFTS
- SECOND ORDER DOPPLER EFFECT
- INHOMOGENEITY OF INTERROGATING FIELDS (BLOCH-SIEGERT EFFECT)
- SECOND ORDER DOPPLER EFFECT
- PHOTON RECOIL

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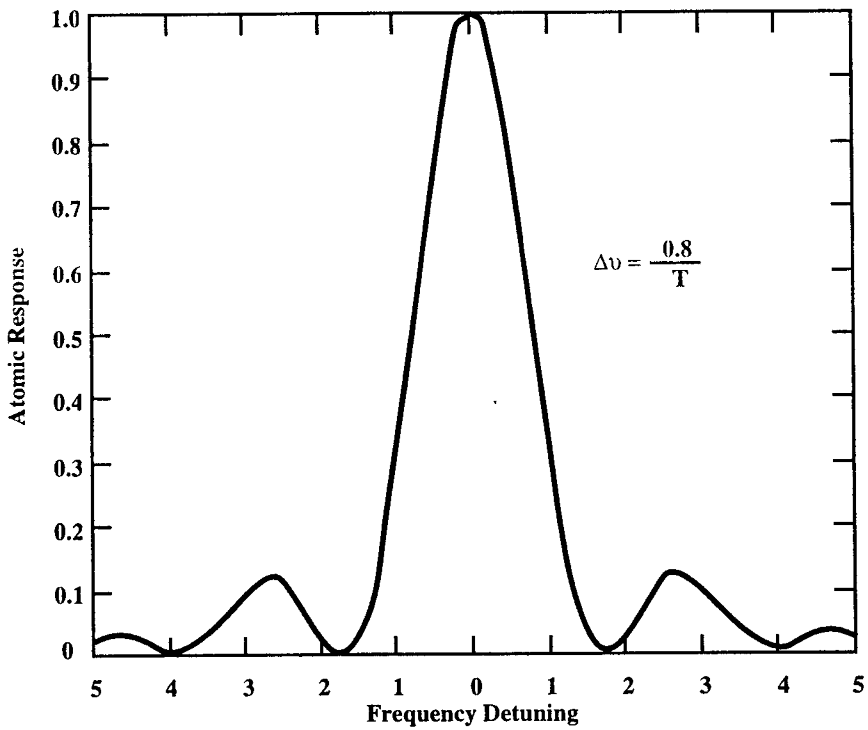
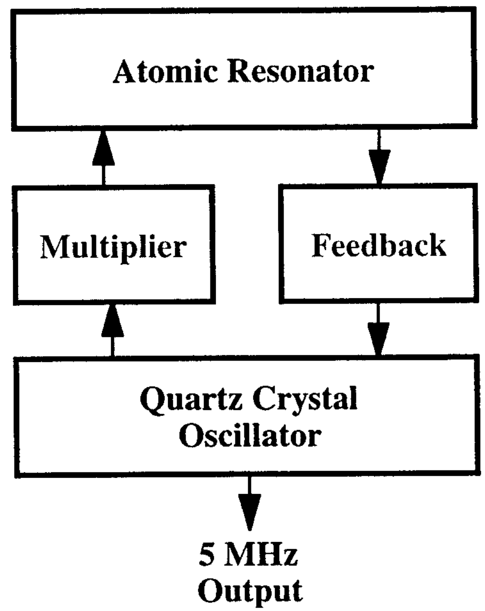
JPL

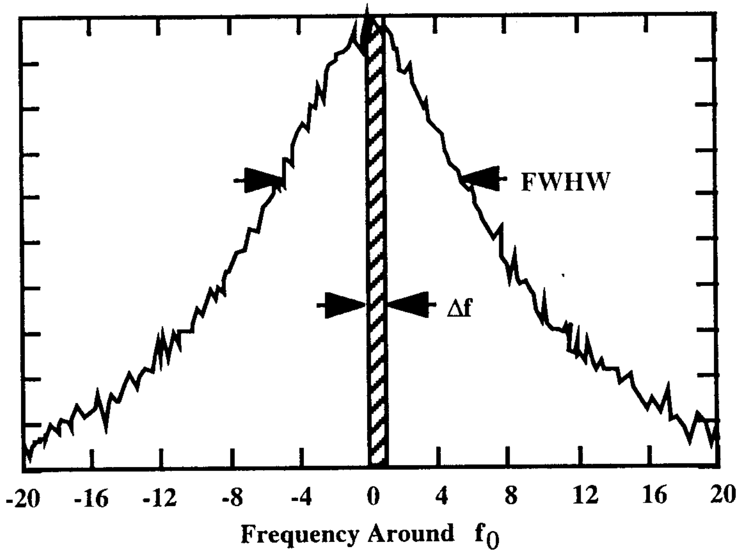
Atomic Frequency Standard





A voltage controlled crystal oscillator (VCXO) is locked to the atomic resonator, a highly stable frequency reference generated from an atomic transition. Of the many atomic transitions available, the ones selected are from those which are least sensitive to environmental effects and which can be conviently locked to the vcxo. The long term stability is determined by the atomic resonator, the short term stability, by the crystal oscillator.

The Importance of Q and SNR



$$\sigma_y \simeq \frac{\Delta f}{f_0} = \left(\frac{FWHM}{f_0}\right)\left(\frac{\Delta f}{FWHM}\right) \propto \frac{1}{Q}\ \frac{1}{SNR}$$

SNR = Signal to noise of detected atomic transition

Q = Quality factor of resonance

Examples	Q	Best σ_y	Number of Atoms
Rb	5×10^7	10^{-13}	5×10^{11}
Cs	$10^7 - 5 \times 10^9$	10^{-14}	
H-Maser	2×10^9	7×10^{-16}	10^{16}
Hg^+	2×10^{12}	$\leq 10^{-15}$	$10^6 - 10^7$

ATOMIC OSCILLATORS

Oscillation occurs when the energy emitted by the atoms during one atomic relaxation time τ exceeds the losses of the microwave cavity used to build up the stimulating field.

Energy emitted in τ = Energy per photon x Number of atoms x Transition prob.

$$= h\nu_{HFS} \times (F\tau) \times (b\tau)^2$$

where $b = 2\pi\mu_0 B_{RF}/h$ and F is the atomic flux.

$$\text{Energy dissipated in } \tau = \frac{\nu\tau}{Q} kB^2_{RF}$$

where $Q \equiv \nu\tau U$/energy lost in time τ and U = energy stored in cavity $= kB^2_{RF}$.

Equating the energy emitted to the energy dissipated yields the oscillation thresh-old.

$$Q > hk / (F\mu^2_0\tau^2)$$

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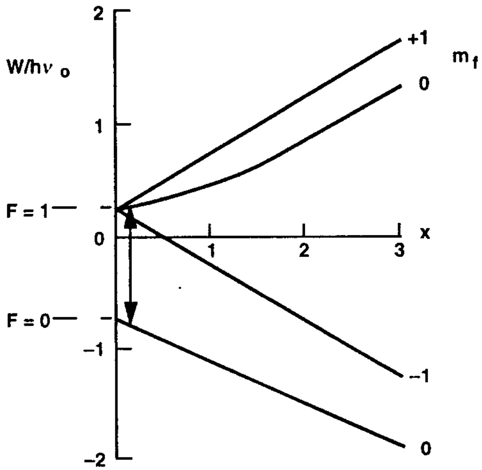

$I = \frac{1}{2}$

^{1}H $x = 1.97 \times 10^{-3}$ Ho

$^{199}Hg^{+}$ $x = 3.72 \times 10^{-4}$ Ho

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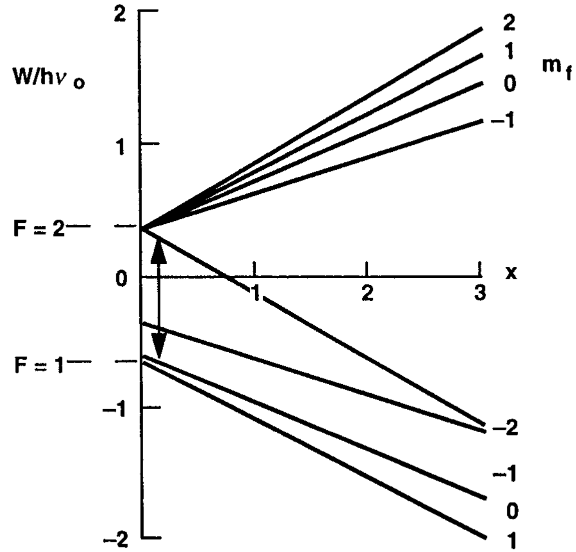

$I = \frac{3}{2}$

^{87}Rb

$x = 4.1 \times 10^{-4}$ Ho

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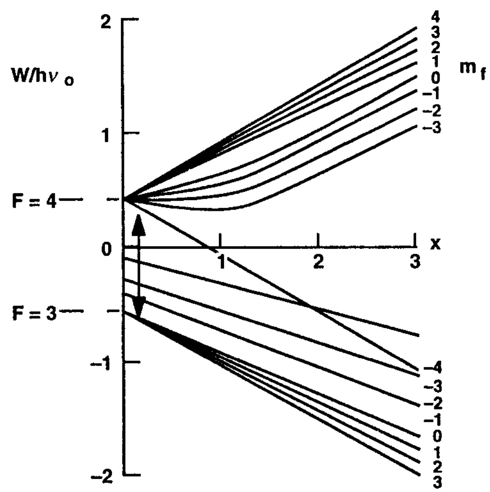


$I = \frac{7}{2}$

^{133}Cs

$x = 3.05 \times 10^{-4}$ Ho

Rubidium Gas Cell Resonator

- The atomic resonance used is at 6,834,682,608 Hz.

- Cell contains Rb gas at ~10^{-6} torr and an inert buffer gas at ~1 torr; Rb atom oscillation lifetime is limited by collisions to ~10^{-2} S; linewidth ~100 Hz; Q ~5 x 10^{7}. Buffer gas, a mixture of positive (e.g., Ar) pressure-shift gases, provides zero temperature coefficient at some T, confines Rb atoms to small region to reduce wall-collision and 1st order Doppler effects.

- Optical pumping relies on the natural coincidence of optical resonance frequencies between ^{85}Rb and ^{87}Rb, both at 795 nm.

- Rf excited ^{87}Rb lamp emits wavelengths corresponding to both the F=1 and F=2 transitions; ^{85}Rb filter cell absorbs more of the F=2 transition light; light which passes through filter is absorbed by the ^{87}Rb F=1 state; excited atoms relax to both the F-=1 and F=2 states, but the F=1 states are excited again; F=2 state is overpopulated; 6.8 Ghz converts F=2 back to F=1, which provides more atoms to absorb light. Microwave resonance causes increased light absorption, i.e., a (<1%) dip in the light detected by the photocell; microwave frequency is licked to photocell detection dip, thus the atomic transition frequency controls the microwave frequency, i.e., the frequency of the crystal oscillator.

Cesium-Beam Frequency Standard

- The atomic resonance used is at 9,192,631,770 Hz - by definition (of the second).

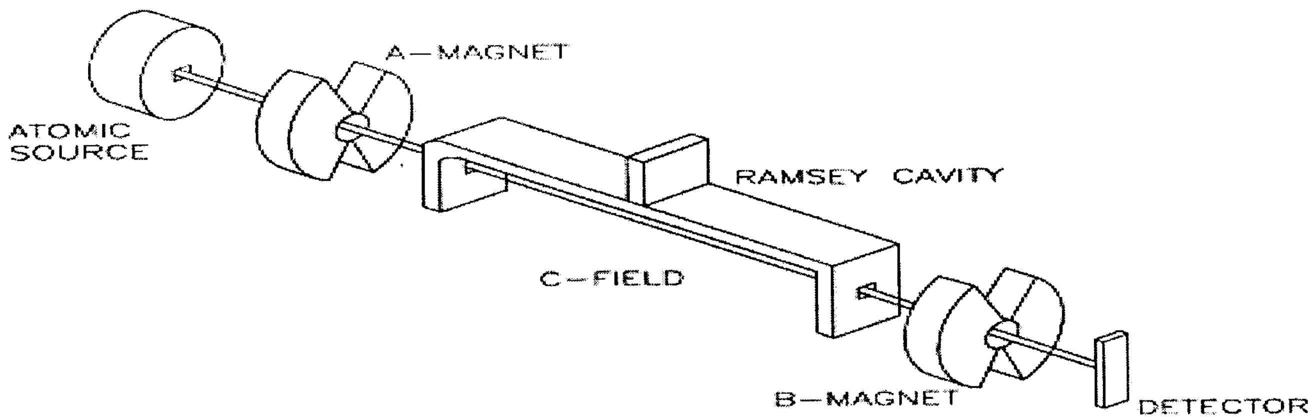
- Oven is at ~100°C, Cs pressure in the oven ~10^{-3} torr, cavity is at ~10^{-9} torr; typical atom speed is 100 m/s; typical cavity length in commercial standards is 10 to 20 cm; interaction time ~1 to 2 x 10^{-3} s; linewidth ~0.5 to 1 kHz; Q ~10^{7}; in standard lab's, length ~4 meter, Q ~108.

- It would be desirable to operate at zero magnetic field - all transitions would behave as a single transition, signal would be 7X larger, but that would require <10^{-8} gauss for errors <1 x 10^{-12}; not feasible; C-field must be applied; a 0.06 gauss C-field separates the sublevels by 40 kHz.

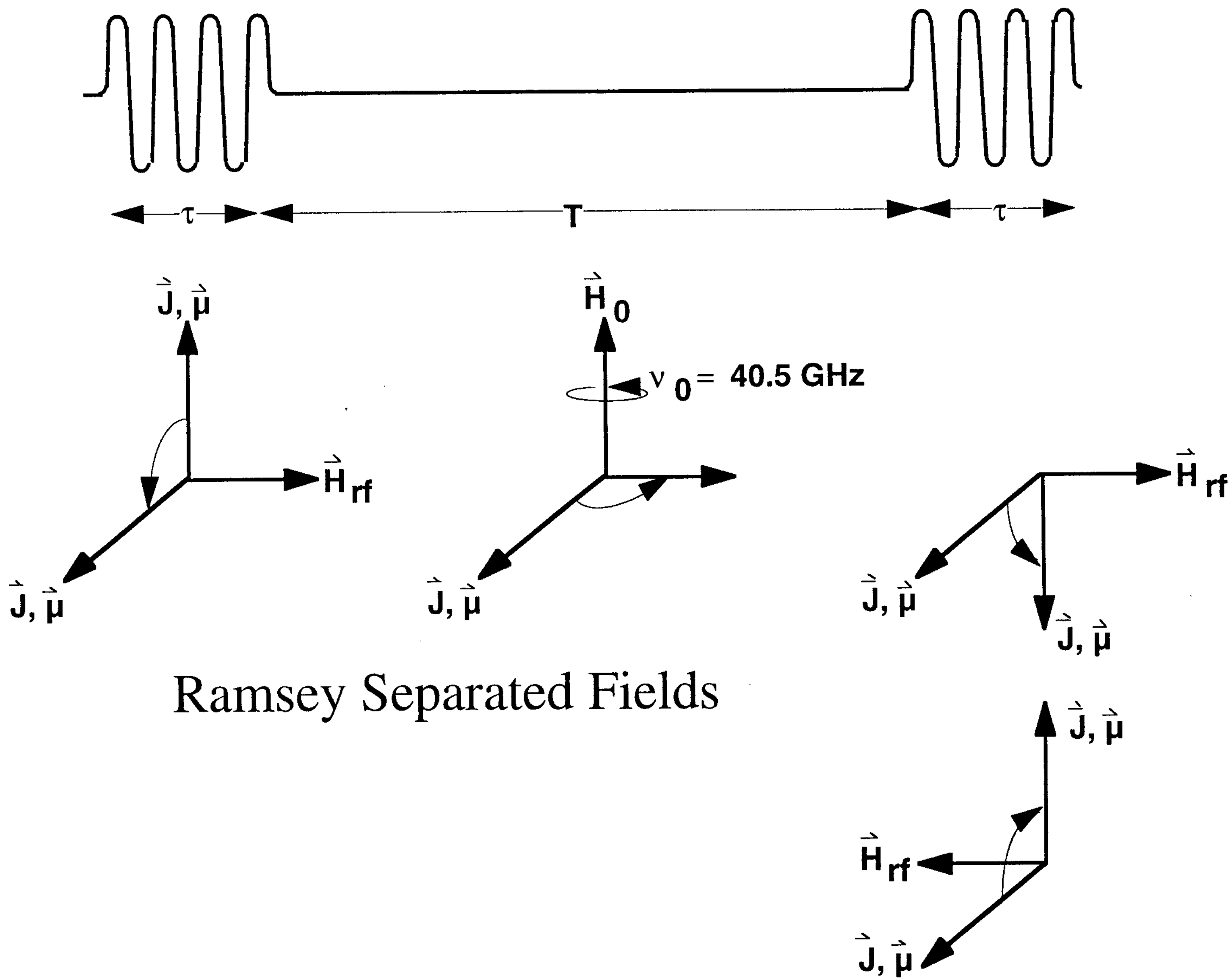
- The (3,0) to (4,0) clock transition has a small quadratic dependence on magnetic field; C-field must be stable and uniform; high degree of shielding is required for $\pm 1x10^{-13}$/gauss (e.g., the HP 004 uses a triple shield).

- State selecting magnet A "selects" one of the two atomic levels; the applied microwave causes a state change; the second magnet deflects to the detector the atoms which have undergone the state change; A and B magnets' peak field ~ 10 kgauss.

- Atom detector is a ribbon or wire (e.g., W or Pt) at ~900°C; Cs atoms are ionized, ions are collected, current is amplified and fed back into feedback network; microwave frequency is locked to the frequency of maximum ion current, thus the atomic transition frequency controls the microwave frequency, i.e., the frequency of the crystal oscillator. Much less than 1% of the Cs atoms


A—MAGNET
ATOMIC
SOURCE
RAMSEY CAVITY
C—FIELD
B—MAGNET
DETECTOR

JPL



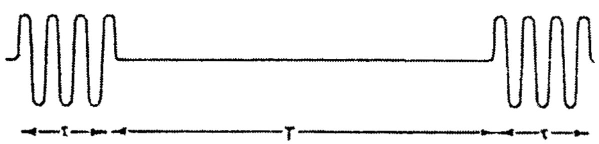
Ramsey Separated Fields

Separated Oscillatory Fields
(Cesium, Trapped Ion)

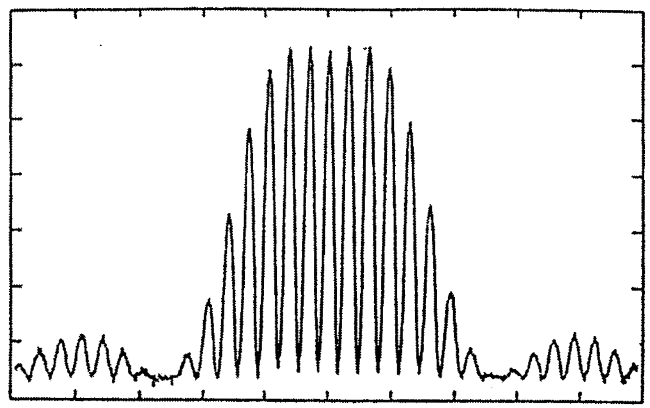
The first neighboring peaks near the central resonance in atomic response vs. frequency correspond to an angular frequency detuning $\Delta\omega$ between the atomic resonator and the interrogating field from the LO such that during the drift time T a phase difference of $\pm 2\pi$ is built up, $\Delta\omega T = \pm 2\pi$.

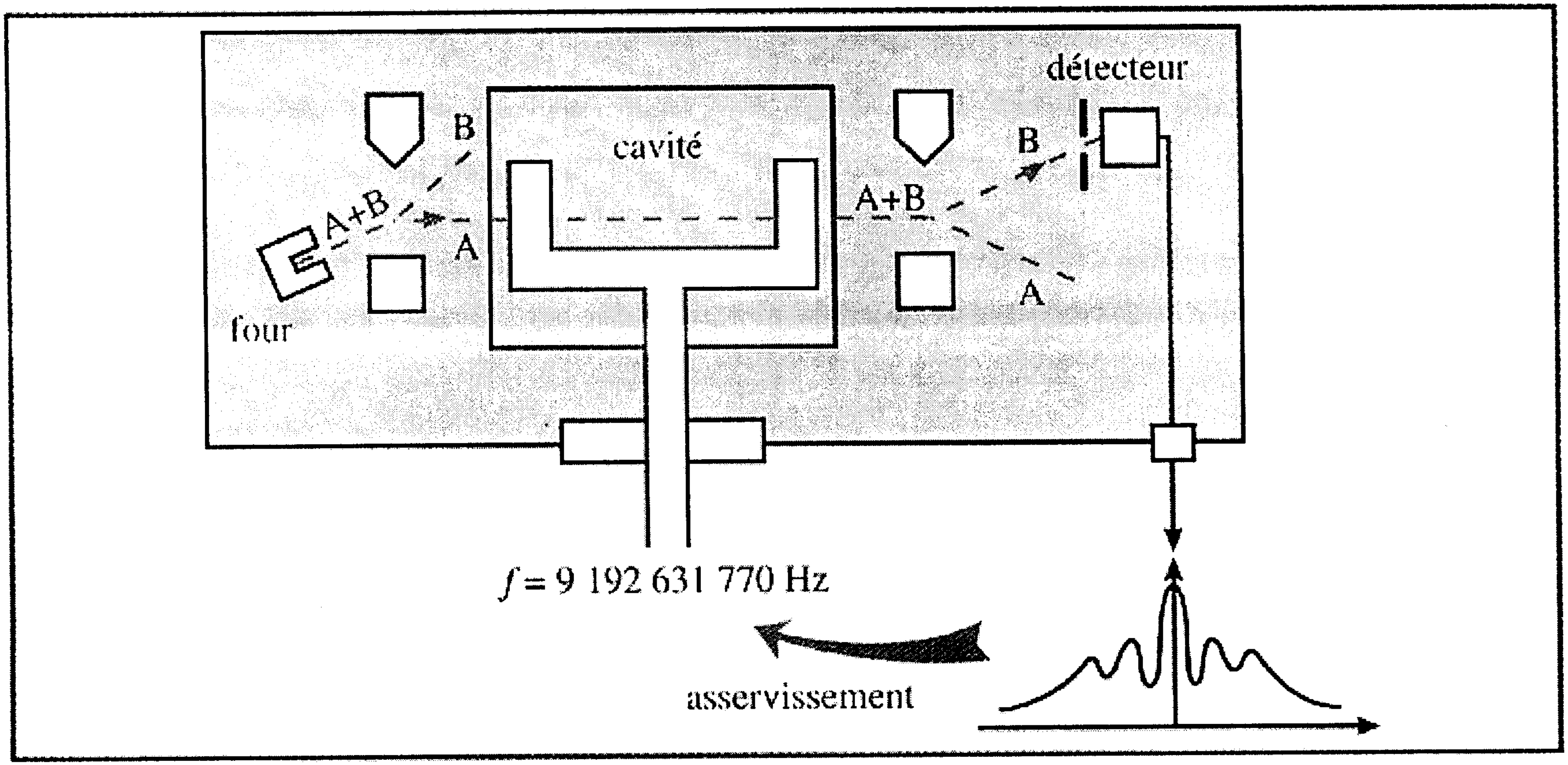
The first neighboring zeroes in atomic response vs. frequency similarly correspond to $\Delta\omega T = \pm\pi$, that is, the second microwave pulse is $\pm\pi$ out of phase with the first pulse and exactly reverses its action on the atom.

TIME DOMAIN MICROWAVE PULSE APPLIED TO THE ATOMS



FREQUENCY DOMAIN ATOMIC RESPONSE





Outline of the cesium beam clock

From LPTF, Paris, France

Hydrogen Maser Frequency Standard

- The H-maser is an active atomic oscillator where a flux of "excited" state atoms enter a cavity resonator tuned to the 1.4 Ghz hyperfine transition. When the energy input into the high Q cavity from incoming flux of atoms exceeds the cavity losses there will be a sustained oscillation at 1.4 Ghz. In operation, the power coupled out of the cavity at is about -96dbm $\approx 2.5\text{x}10^{-13}$ Watt = .25 picowatt.

- H_2 molecules are dissociated in an rf discharge and form a collimated beam of hydrogen atoms which pass through a multi-pole magnetic state selector. H atoms in the upper hyperfine state are focused into the maser bulb while lower state atoms are de-focused so that few enter the bulb. This creates the population inversion necessary for maser action.

- Atoms enter the cavity and interact coherently with the stimulating radiation for a second. The walls of the confinement bulb are coated with teflon to prevent loss of phase coherence between the atom and the oscillating magnetic field of the cavity. The collisions do lead to a wall shift of the atomic resonance which changes over time and leads to a long term drift of the maser output frequency ($\approx 10^{-15}$/day).

- H-masers are currently the most stable frequency standard for averaging times between 10^3 and 10^4 seconds where stabilities as good as $7\text{x}10^{-16}$ are reached.

History of Laser Cooling of Neutral Atoms

* 1933: Deflection of Sodium atoms observed by Frisch.
* 1975: Cooling of neutral atoms with counter-propagating laser beams proposed by Hansch and Schawlaw.
* 1983: Slowing of atomic beams observed by Phillips et. al. and Hall et. al.
* 1985: First observation of laser cooling in three dimensions in an "optical Molasses" by Chu et. al.
* 1986: First observation of a magneto-optical trap by Chu, Pritchard et. al.
* 1995: First observation of Bose-Einstein condensation by Cornell, Weiman, et. al.

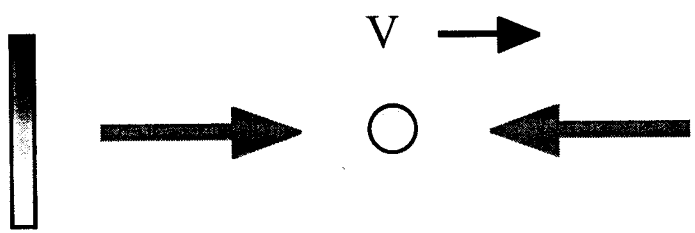
Advantage of laser cooled clocks

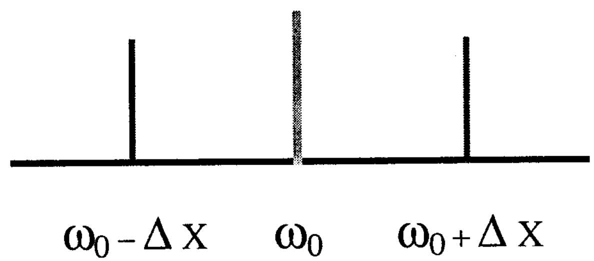
- Laser cooling reduces the speed of atoms, and increases the interaction time of atoms with the microwave fields
  - Reduces linewidth of transition
  - Reduces fundamental limitations to accuracy
  - Allows the use of techniques associated with use of lasers, such as optical pumping for state slection
  - Allows better control of environmental perturbations
  - Generally increases signal to noise ratio, and thus increases stability

Principles of Laser Cooling and Trapping

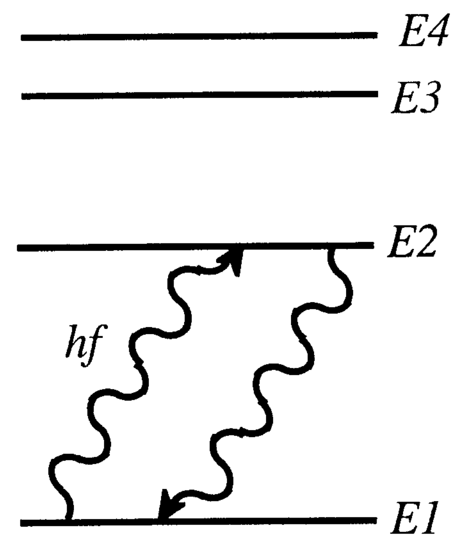
- Before 1980, laser radiation could only be used to control a change in the internal structure of the atom (occupation of the state) -- $\Delta E = h\nu$
- After 1980, laser radiation could be used to control the external degrees of freedom of the atom (momentum)
  - Light carries momentum $hk/2\pi$
  - Atomic momentum (motion) can be changed upon absorption or emission of a photon
  - Absorption of light depends on an atom's velocity (Doppler effect). Origin of cooling force.
  - Absorption of light depends on the magnetic field in which atom finds itself (Zeeman effect). Origin of trapping force.

Laser Cooling of Atoms





$$f = f_0 \left(1 \pm \frac{v}{c}\right)$$



$$E_2 - E_1 = hf$$

Principles of Laser Cooling and Trapping

- Key to laser cooling is the high flux of photons combined with high resonant scattering rates of strong dipole transitions

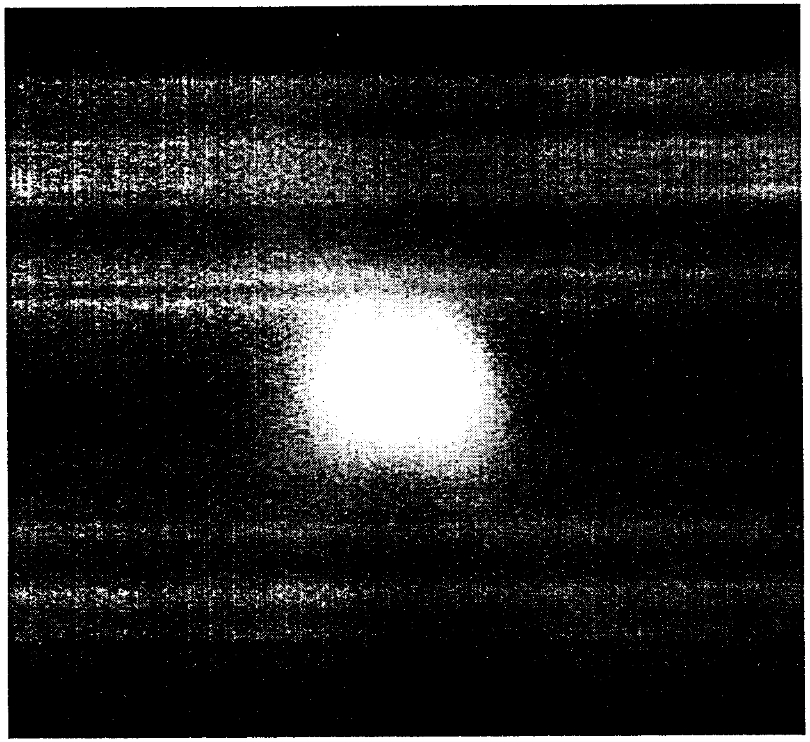
  $$\Gamma_{SC} = \frac{\Gamma}{2}\left(\frac{I/I_{sat}}{1 + I/I_{sat} + 4\delta^2/\Gamma^2}\right)$$

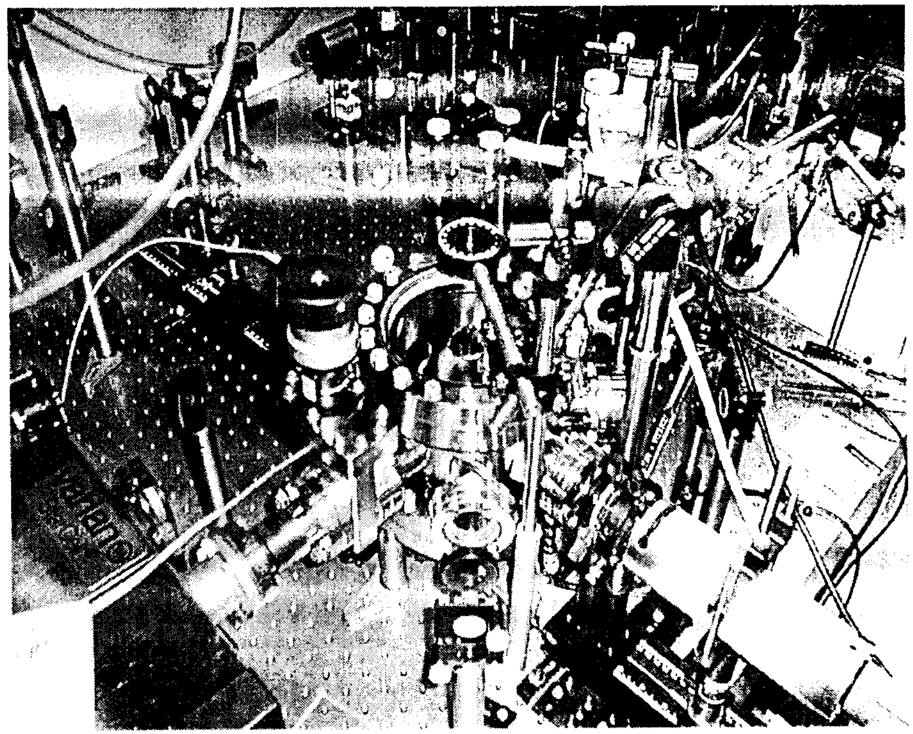
  Here, Γ is the natural linewidth, $\delta = \omega_l - \omega_0$

  - For Rb, 0 to 60 mph in 300 μs!
- Photon scattering involves random fluctuations: Atoms heat
- Using cooling, heating, a sample of atoms settle to a Maxwell-Boltzman steady state velocity distribution
- We get a Doppler temperature: $T_D = h\Gamma/\pi k_B$ (Doppler cooling limit)
- Sub-Doppler cooling can be obtained by "induced orientation" in the ground state of the atom, limited to a few times recoil temperature,

  $T_r=(h^2k^2/4\pi^2 mk_B)$

Cooled Cesium Atoms





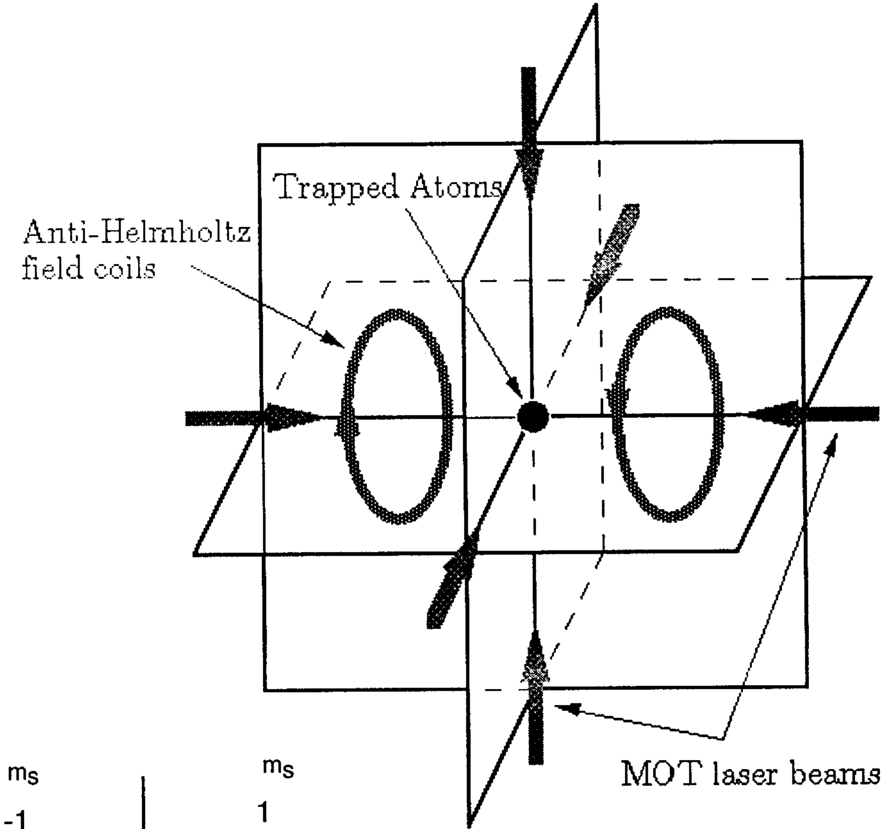
- $N = 10^7$
- $T = 20\ \mu K$

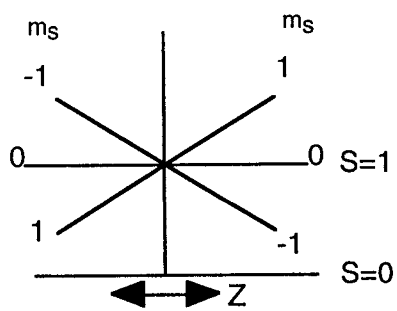
The Magneto-optical trap (MOT)

- Atomic levels in an inhomogeneous Magnetic field

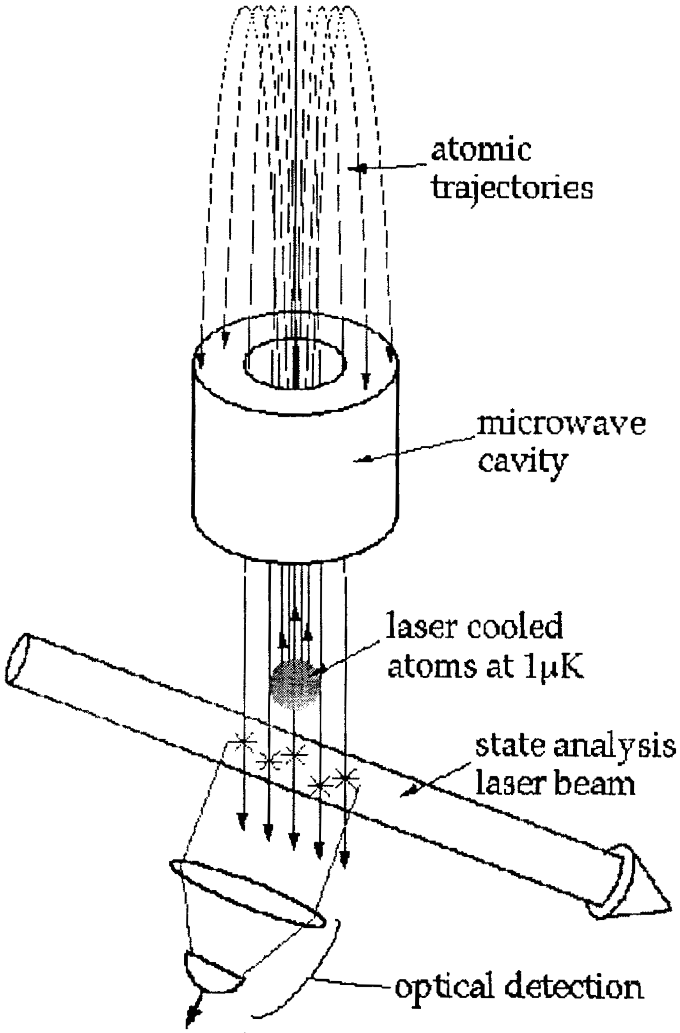
- The MOT consists of three pairs of counter-propagating circularly polarized light beams in a spatially varying magnetic field generated by a pair of anti-Helmholtz coils

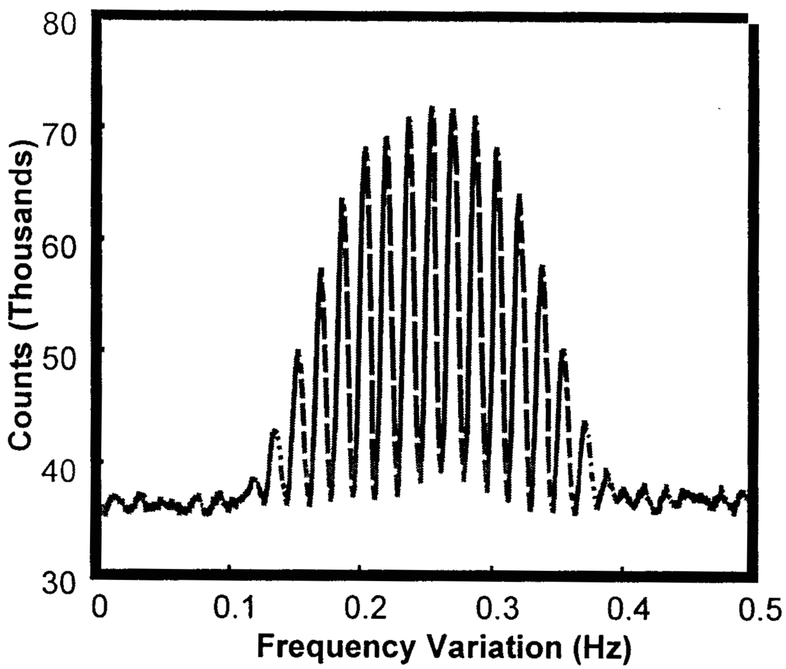
- An atom always absorbs light from laser beams pushing it back to the center of the trap

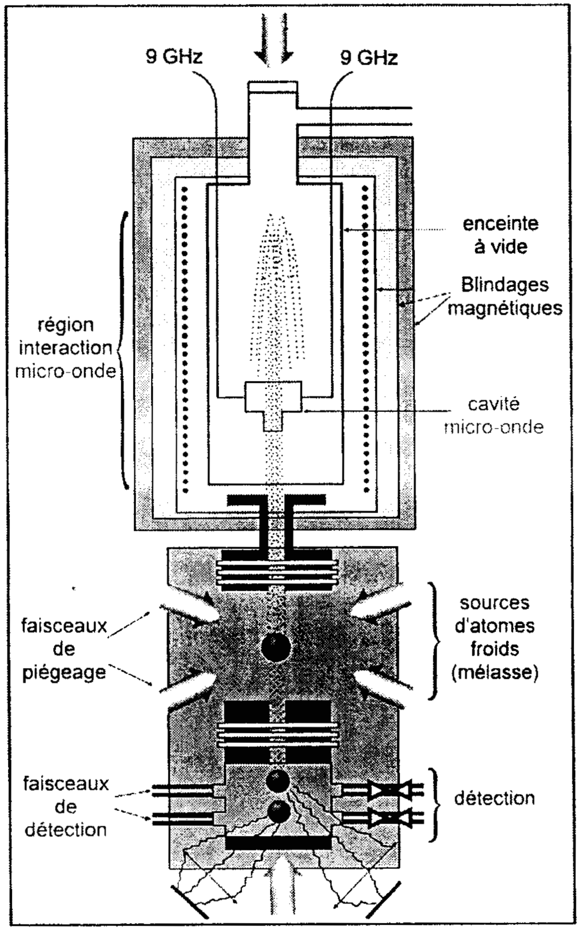




Atomic Clocks: Temporal Interferometers







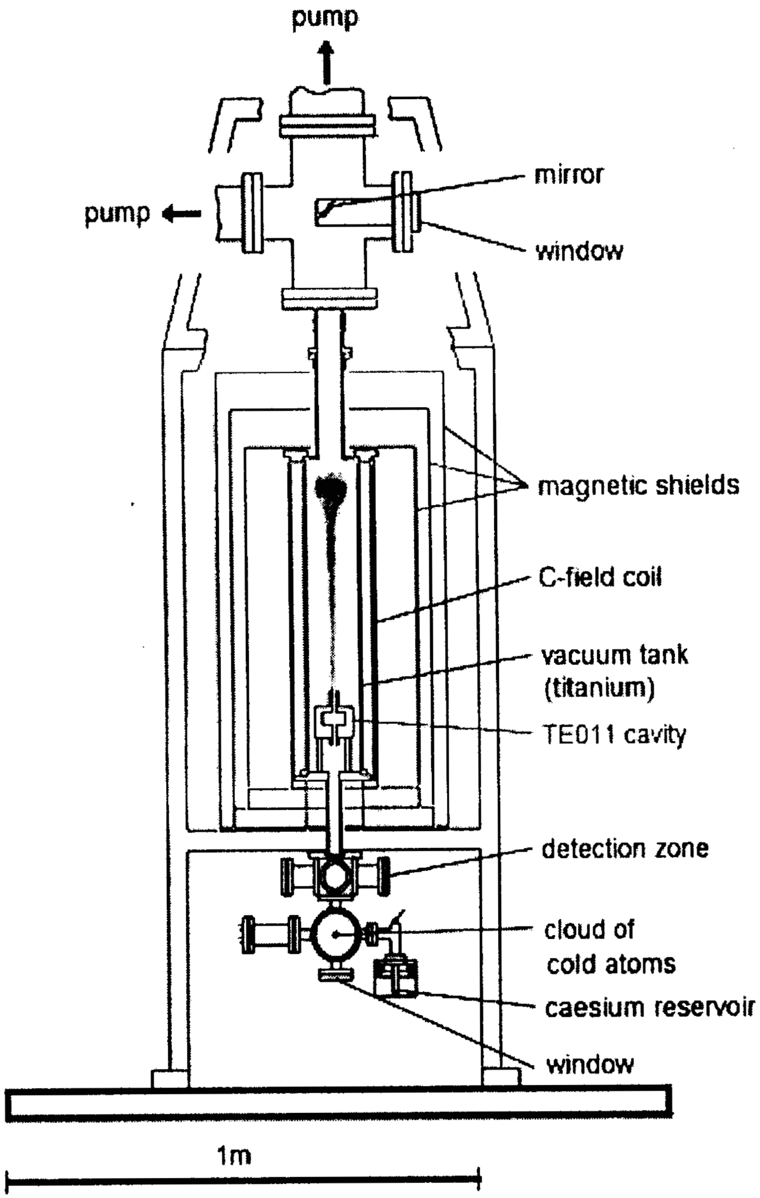
LPTF Cesium Fountain Clock

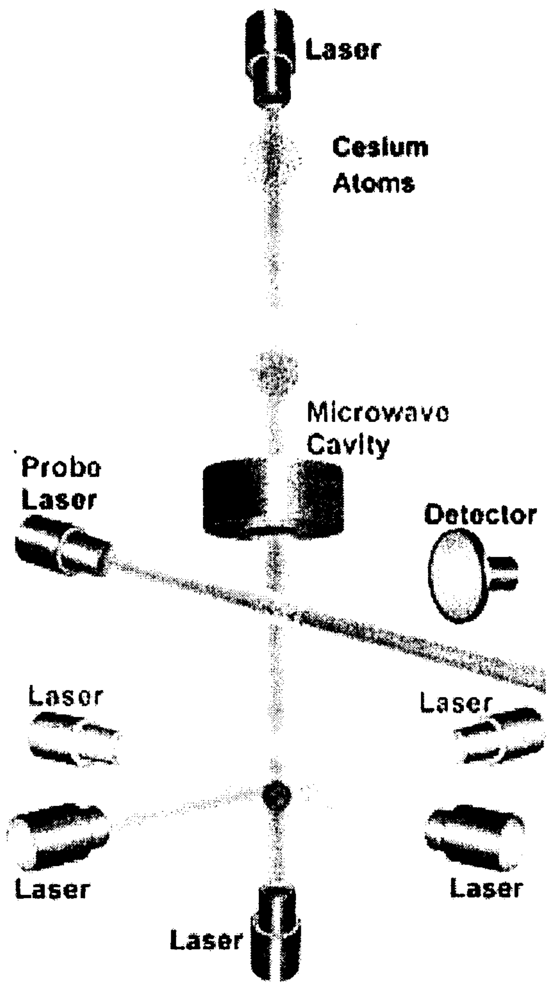
Accuracy ~ 1.2×10^{-15}

Operational Steps of a Fountain Clock

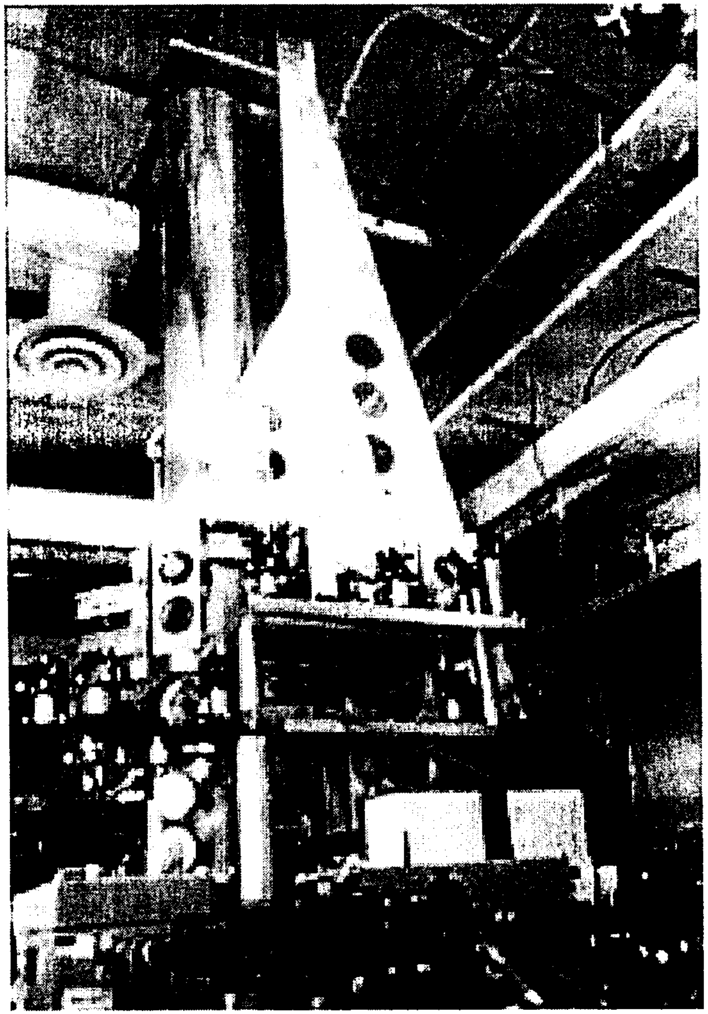
- Trap and cool atoms
  - MOT, molasses from background vapor/beam
- Launch atoms upward (toss up!)
  - Change the upward force by changing laser frequency
- Observe clock transition
  - Count atoms by laser fluorescence
- Feedback to LO

PTB Caesium-Fountain

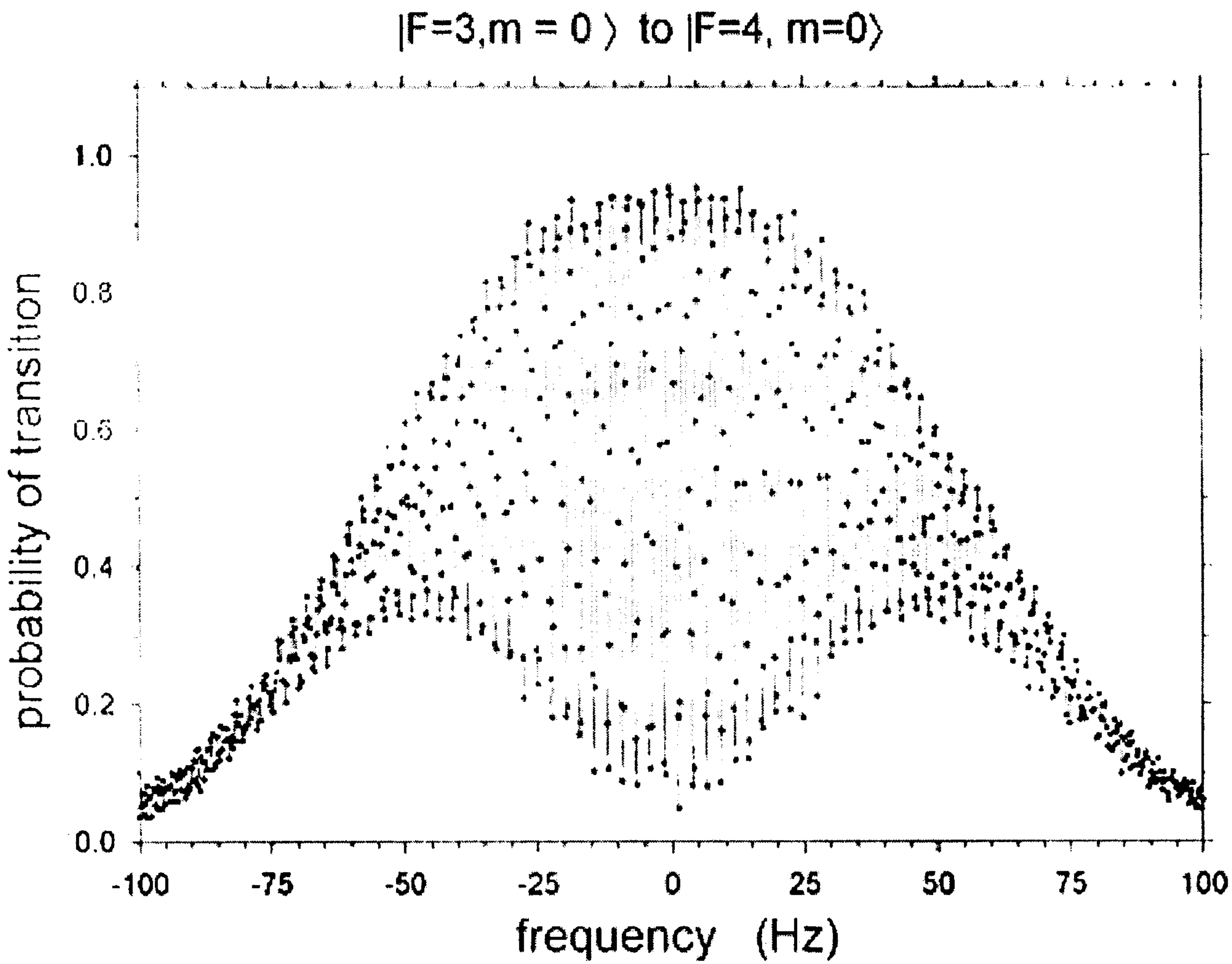



Laser
Cesium
Atoms
Microwave
Cavity
Probe
Laser
Detector
Laser
Laser
Laser
Laser
Laser

NIST F-1

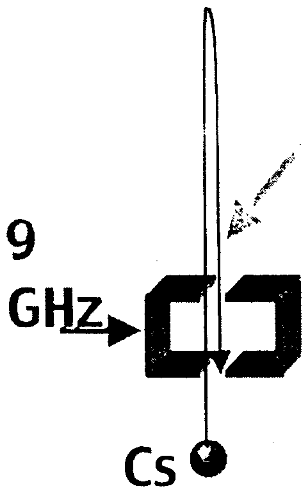


Cesium Fountain at NIST, Boulder



Ramsey fringes from the NIST fountain

Phycical Basis for the Fountain Clock



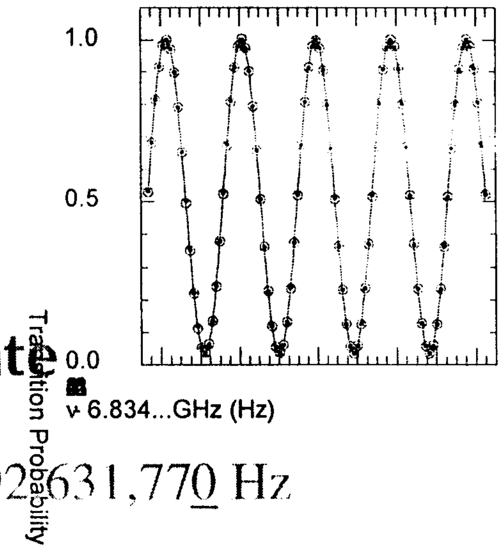
$$\Psi = \frac{|3\rangle + e^{i2\pi(9GHz)t + i\varphi_c}|4\rangle}{\sqrt{2}}$$

Cs 6s ground state

$|F=4\rangle$

$|F=3\rangle$

$\nu \ldots 9,192,631,770$ Hz



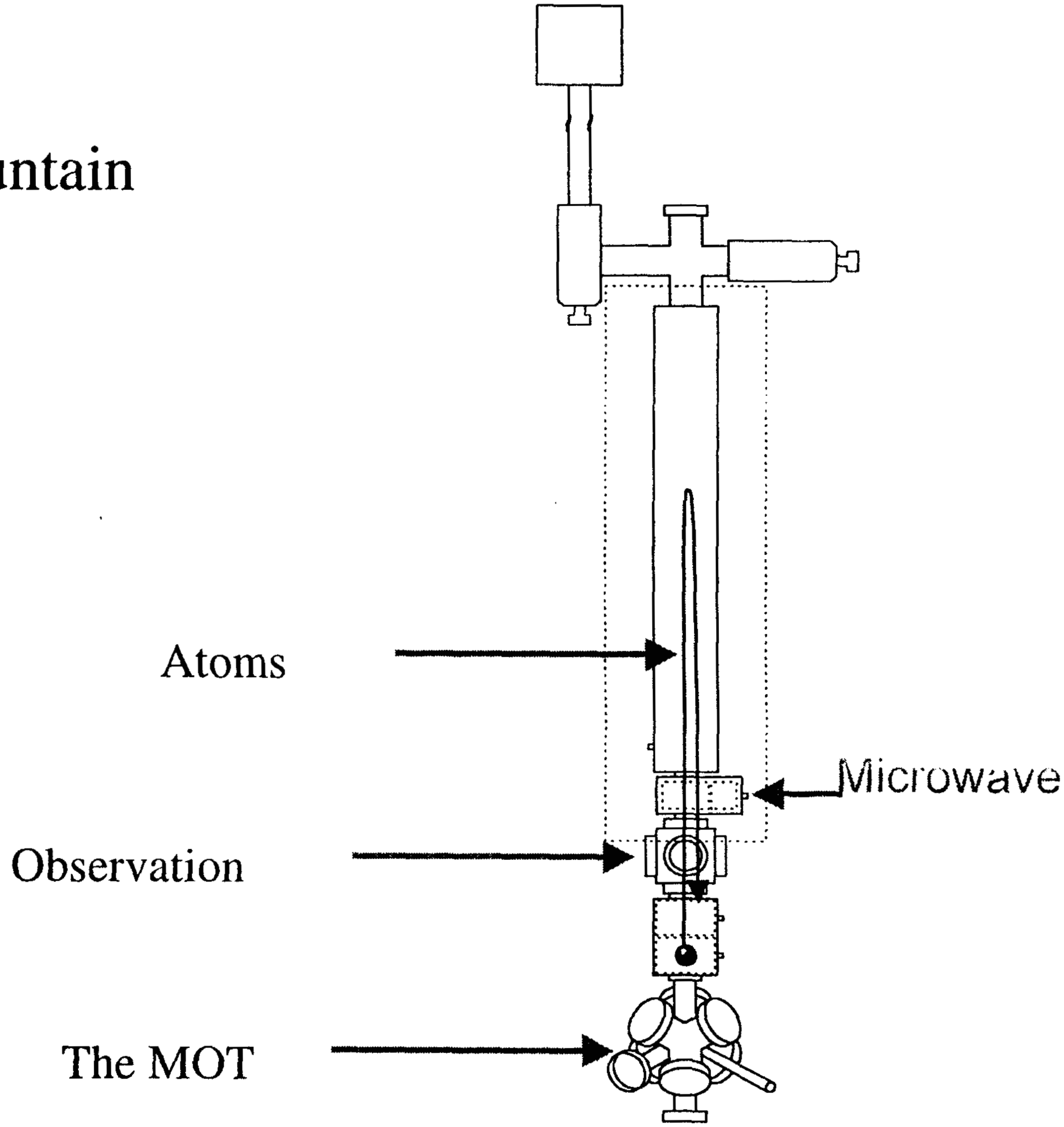
Accuracy of room temperature clocks < 10^{-14}

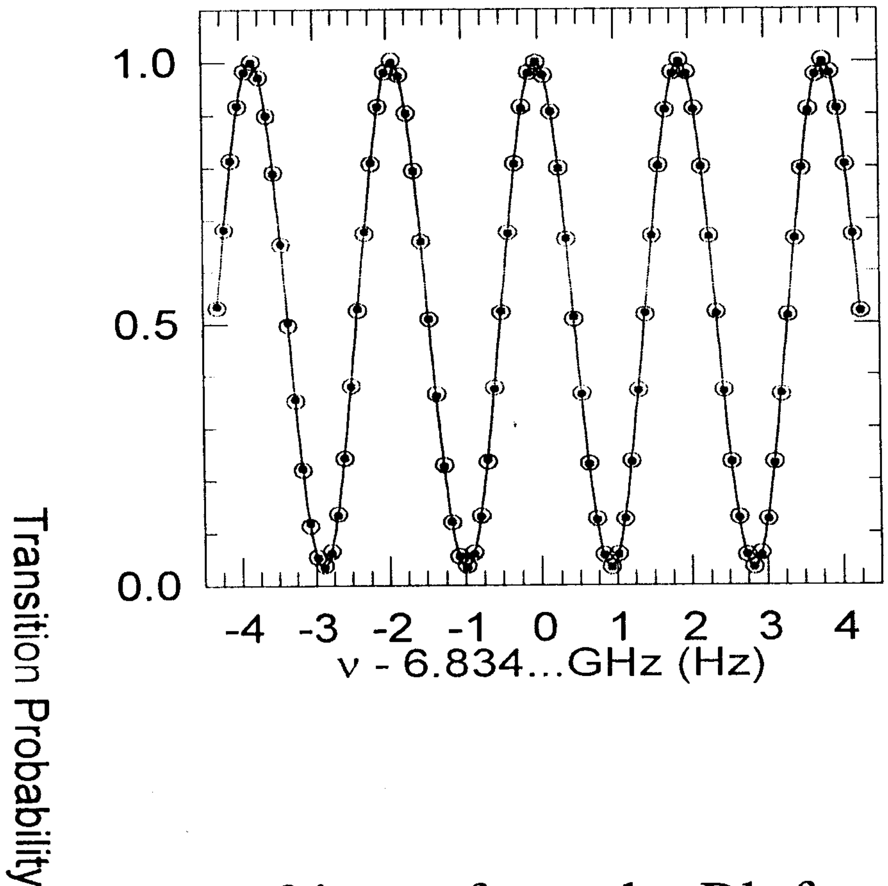
Potential accuracy of cold clocks: 10^{-16} to 10^{-17}

Cold collisions a fundamental limitation:

- Cs cold collision shift = 10^{-12} at n= 10^{9} cm^{3}

Outline of a Fountain





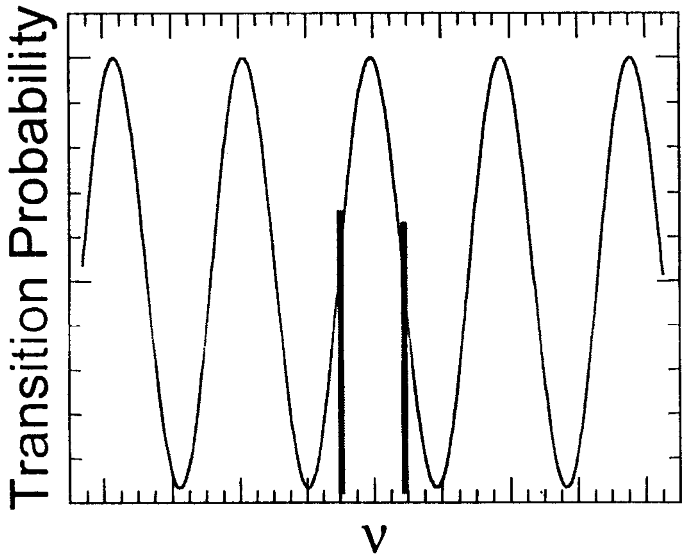
$\Delta\nu = 0.953$ Hz
$\sigma_y(\tau) = 2.1\leftrightarrow 10^{-13}\ \tau^{-1/2}$
S/N = 200:1 (local oscillator)

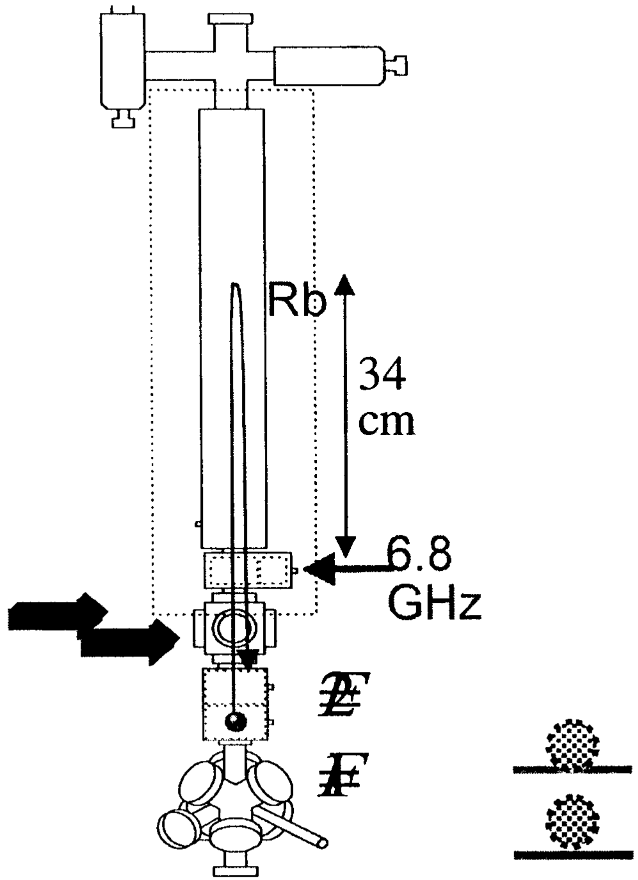
$B_c = 710\ \mu G$ (f_Z =1 kHz)
Ti:Sapphire: 1.4W from fiber
temprature @ 5μK

Ramsey fringes from the Rb fountain at Yale

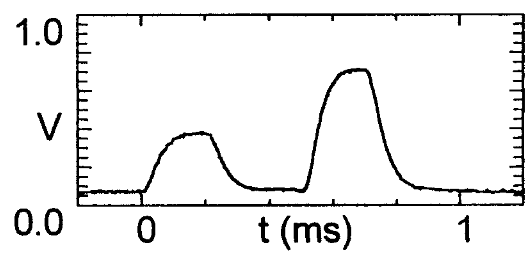
Legere & Gibble, PRL **81,** 5780 (1998)
Gibble, Chang, & Legere, PRL **75,** 2666 (1995)
Myatt, et al., Opt. Lett. **21** 290 (1996)

Atomic State Detection

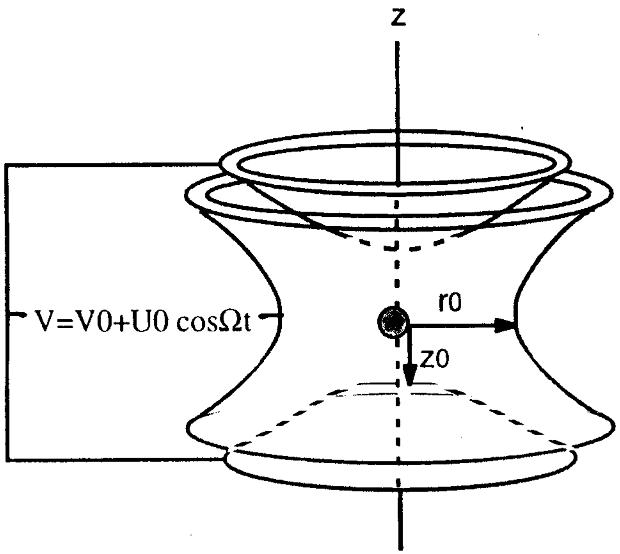




Rb Fountain at Yale

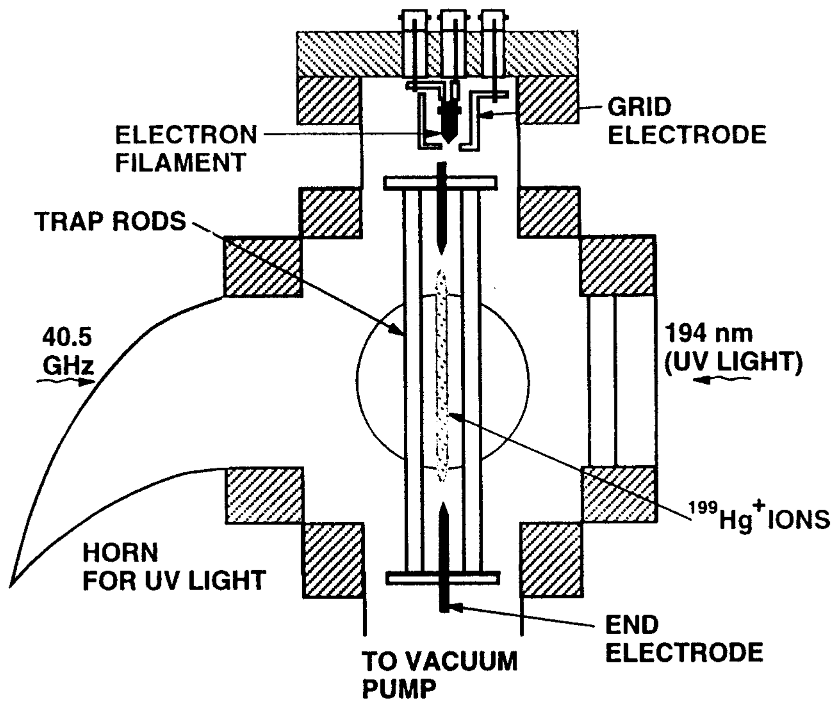


• Detect $N_{F=2}$ then $N_{F=1}$ and normalize.

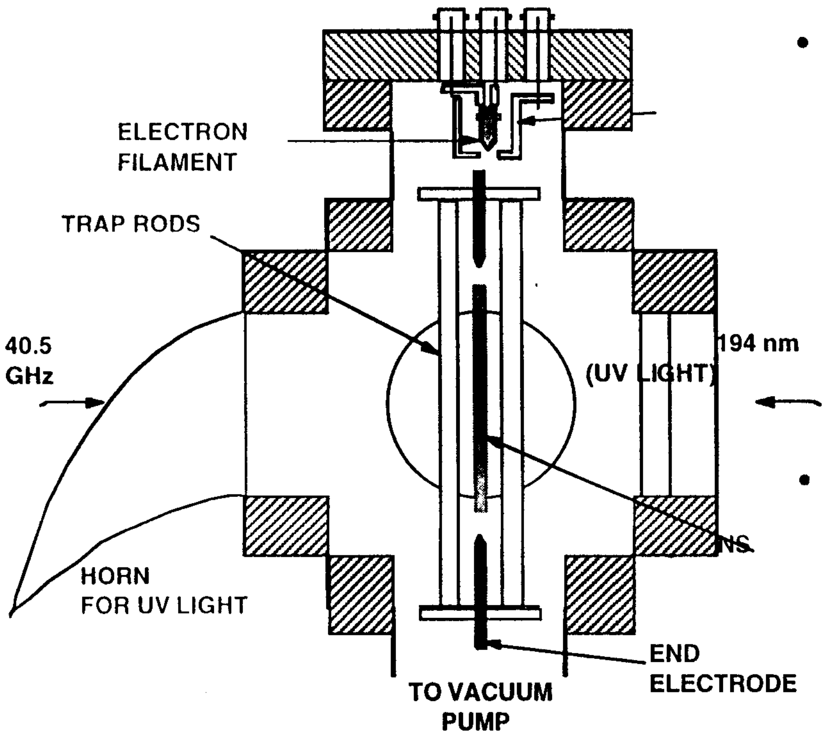


Hyperbolic Ion Trap

Schematic Diagram of the Linear Trap and the Vacuum Cube in JPL's LITS



Linear Ion Trap Standard (LITS)



Schematic Diagram of the Linear Trap

- **Major JPL Innovation: Linear Ion Trap**

  -- Simpler Physical Structure

  -- Increased Signal to Noise Ratio; Stability

  -- Easier to Reproduce

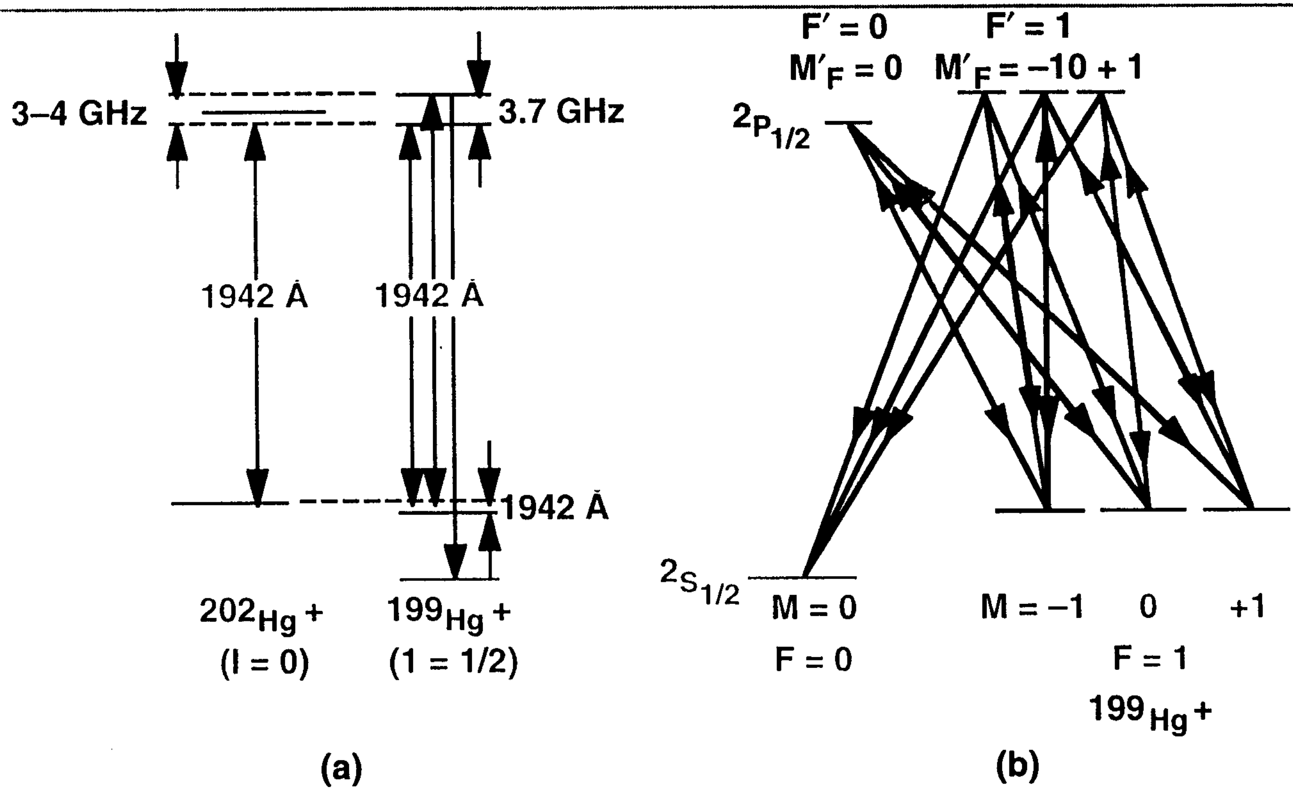
- **Passive Standard Provides Flexibility**

  -- Choice of ions (e.g.. Hg+, Yb+)

  -- Choice of Local Oscillators (e.g. quartz, cryogenic sapphire oscillator)

JPL

STATE SELECTION

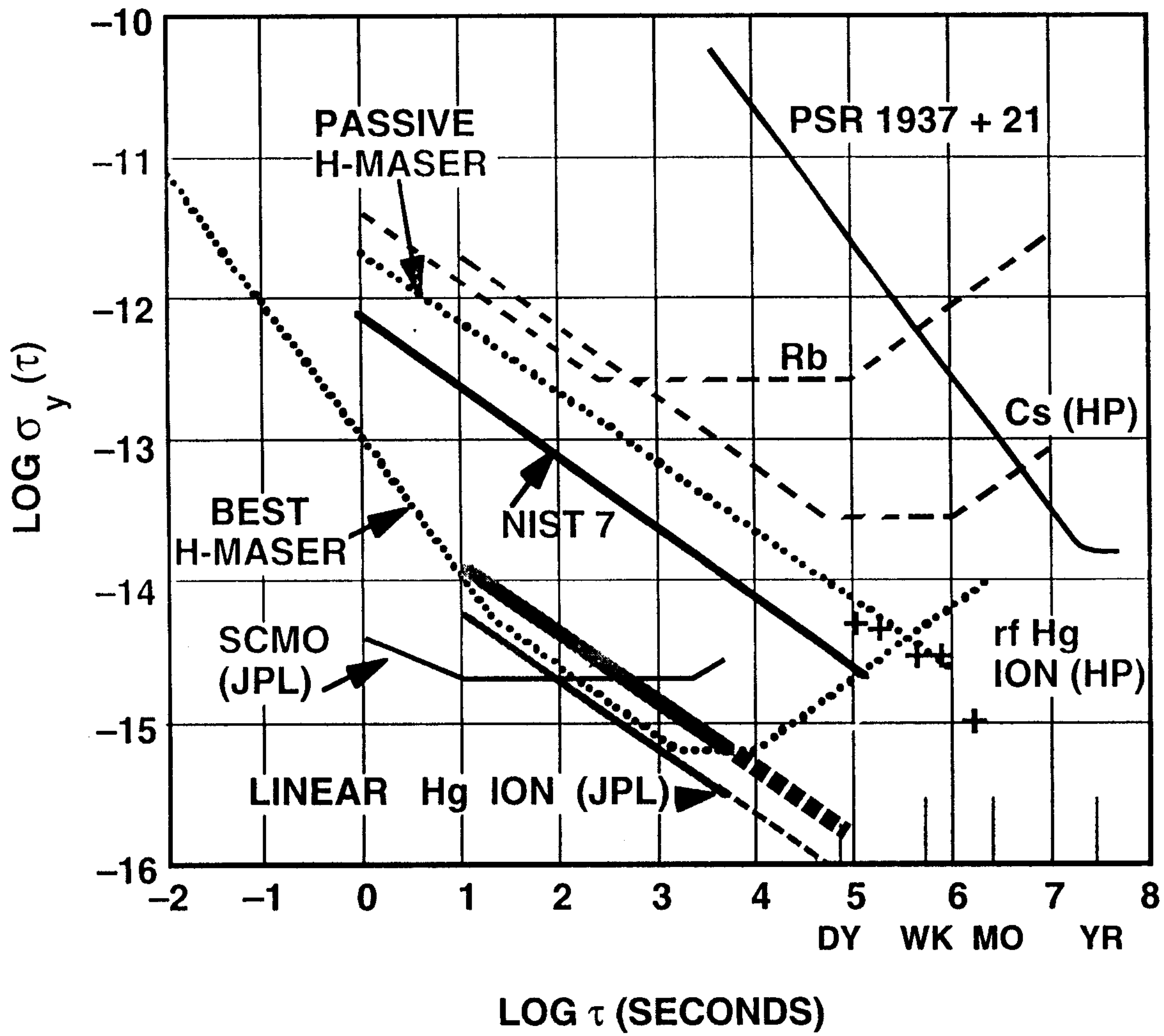


(a) LEVEL STRUCTURE AND (b) OPTICAL PUMPING SCHEME OF Hg^+ IONS

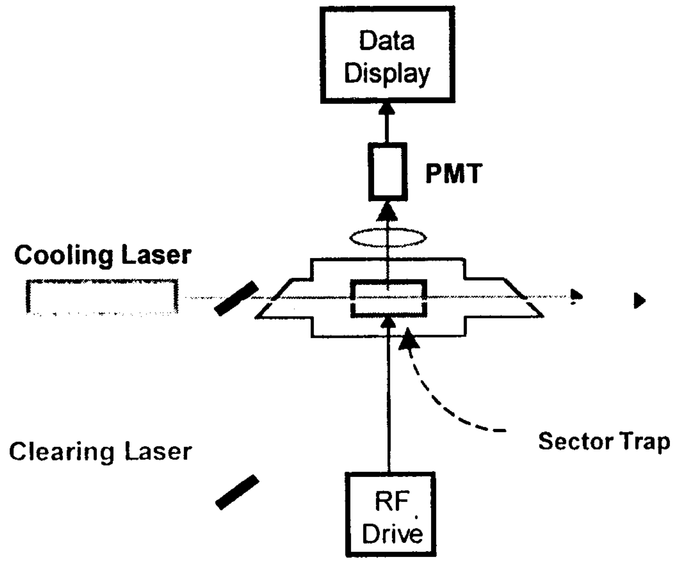
1942 Å LINE FROM ^{202}Hg LAMP WITH WIDTH 3–4 GHz WILL DEPOPULATE F = 1 LEVELS OF GROUND STATE IN ~1/2 SEC WITH FLUX OF $\sim 3 \times 10^{12}$ PER SEC CM^2

Linear Ion Trap Standard (LITS)

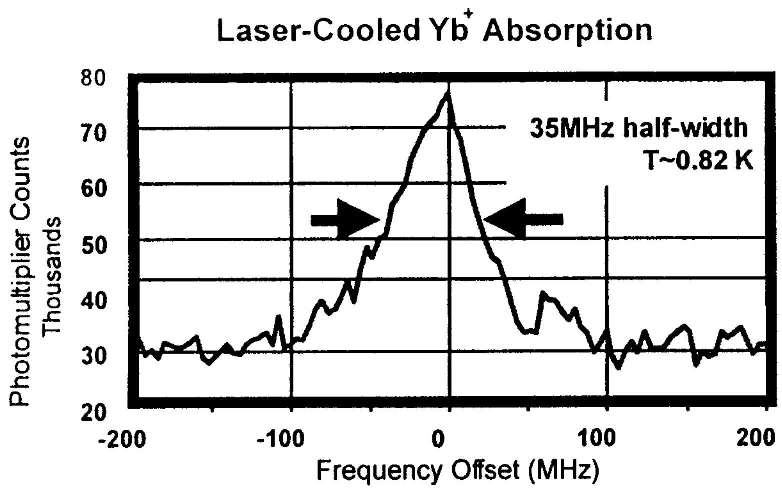
Fractional Frequency Stability



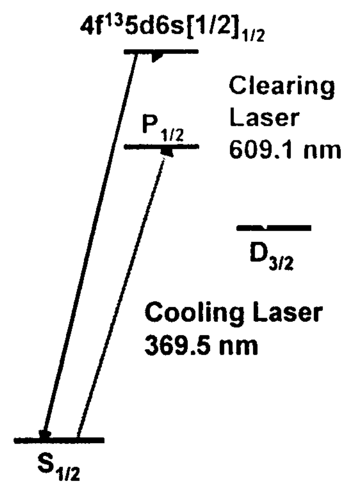
Laser Cooling of Yb^+



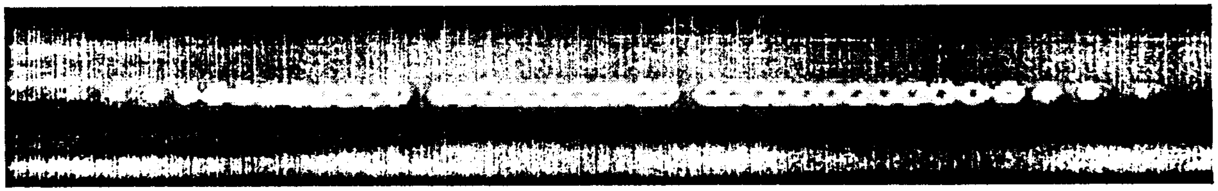
Experimental Configuration

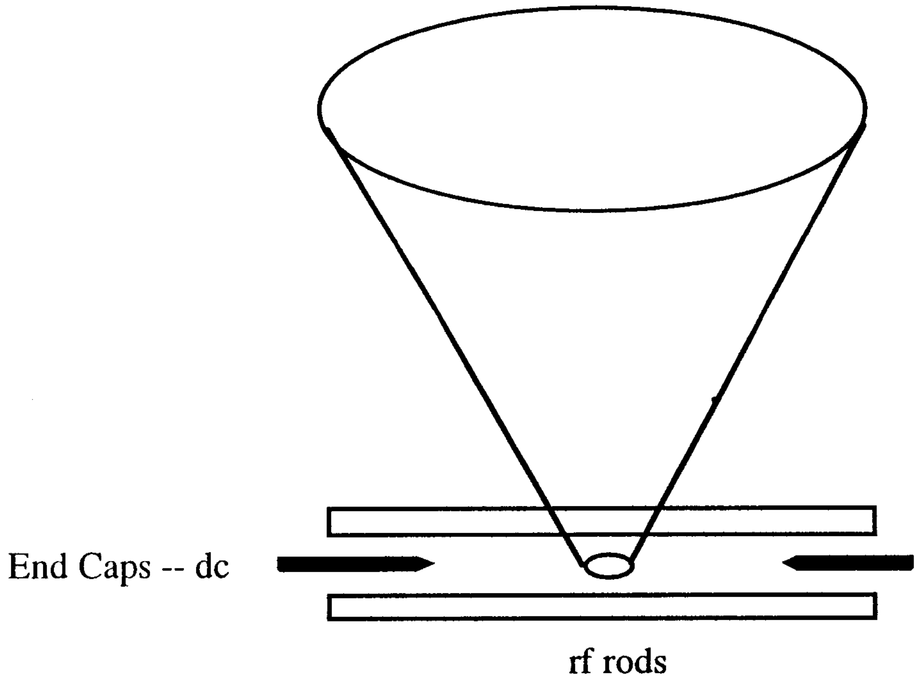


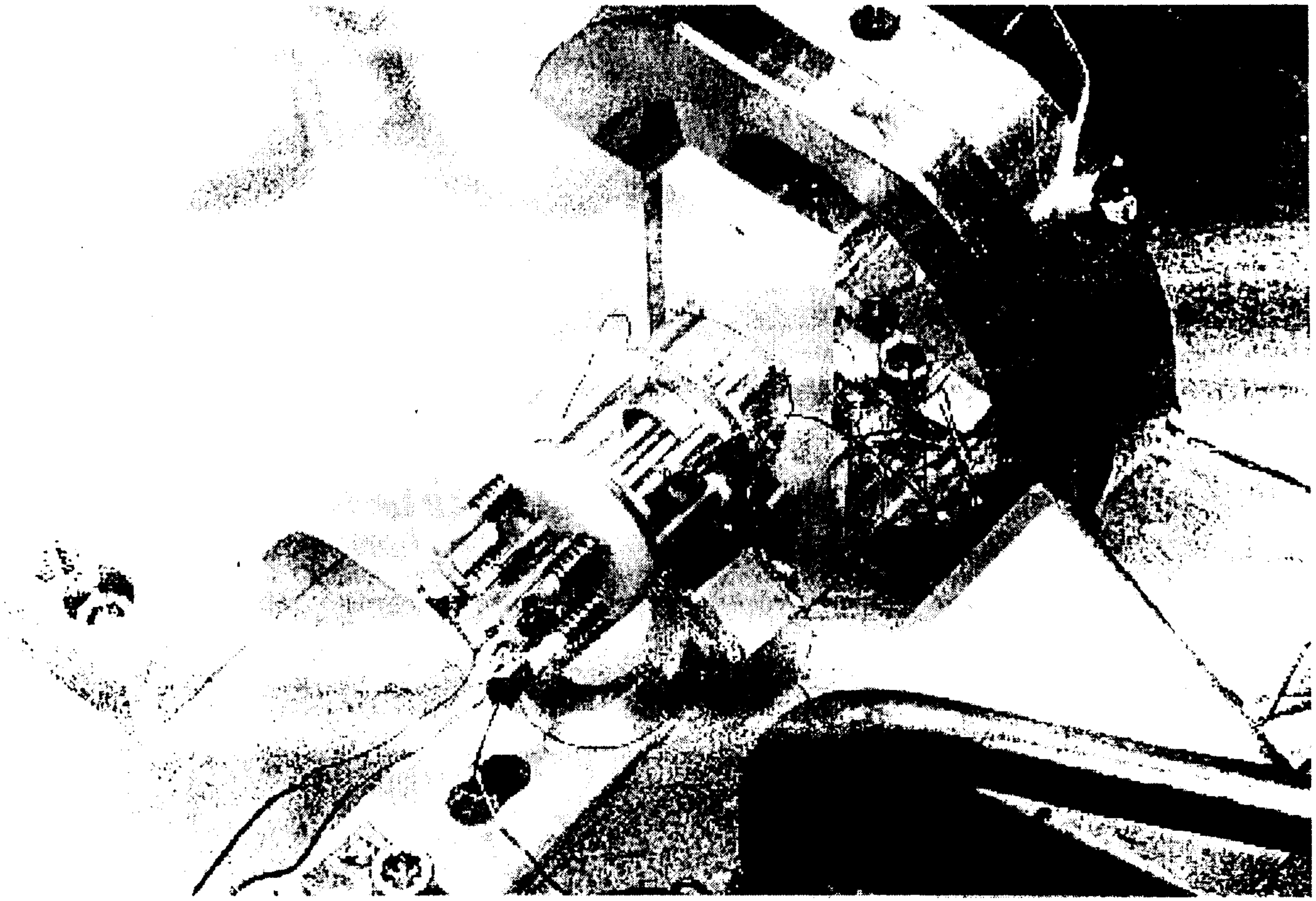
Atomic Level Diagram



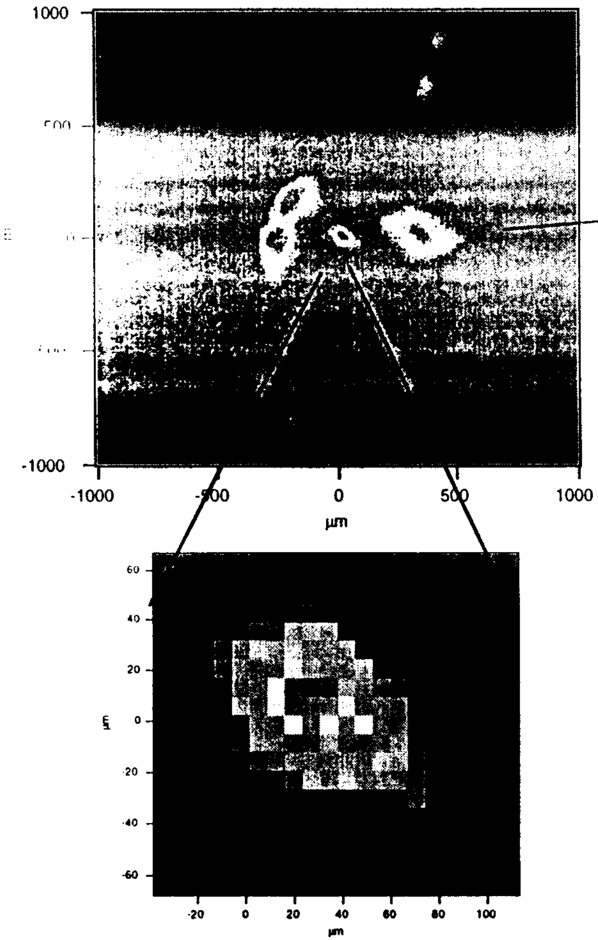
Laser Cooled Ions in a Linear Trap







Paul-Straubel rf trap and single ion image



Single ion fluorescence image

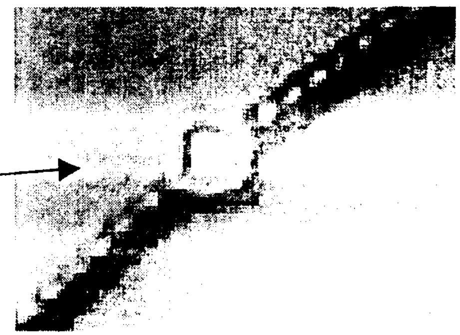
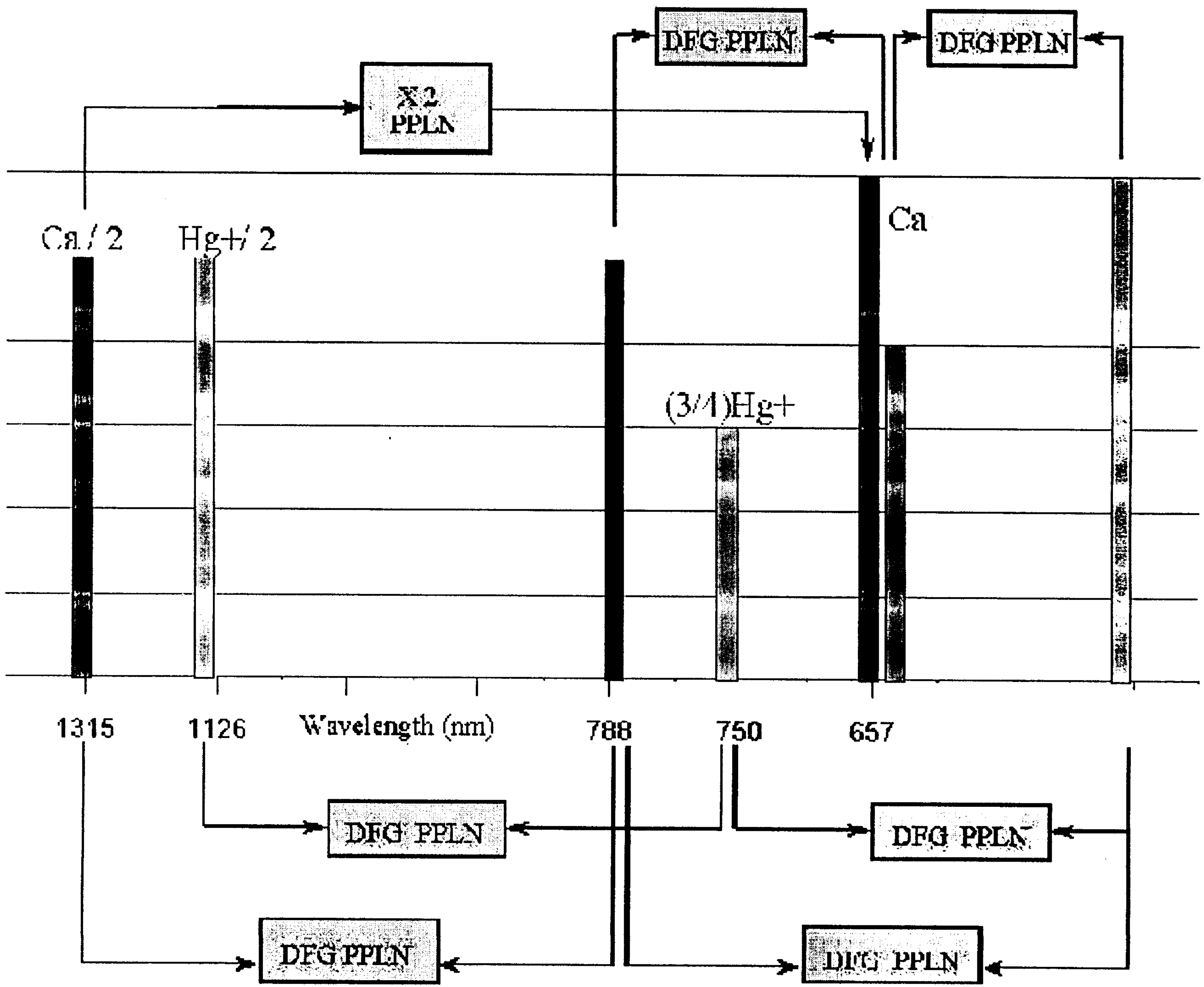


Photo of a Paul-Straubel trap

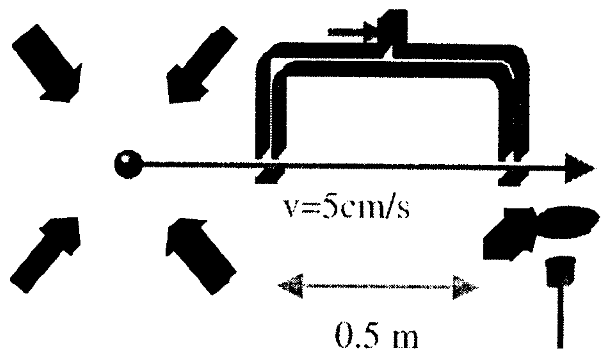
The trap is made of twisted Ta wire loop of 1.0 mm diameter.

The image resolution is limited by the photon collection optics (x4.5).



DFG PPLN
DFG PPLN
X2 PPLN
Ca / 2
Hg+/ 2
Ca
(3/4)Hg+
1315
1126
Wavelength (nm)
788
750
657
DFG PPLN
DFG PPLN
DFG PPLN
DFG PPLN

Space Laser Cooled Clocks



Repeat every 10 s ♦

$$\sigma_y(\tau) = \frac{\Delta\upsilon}{\pi\upsilon \mathrm{S/N}}\sqrt{\frac{T}{\tau}} = 7.3\times10^{-15}\big/\sqrt{\tau}$$

Scaling of $\sigma_y(\tau=1\mathrm{s})$ with T

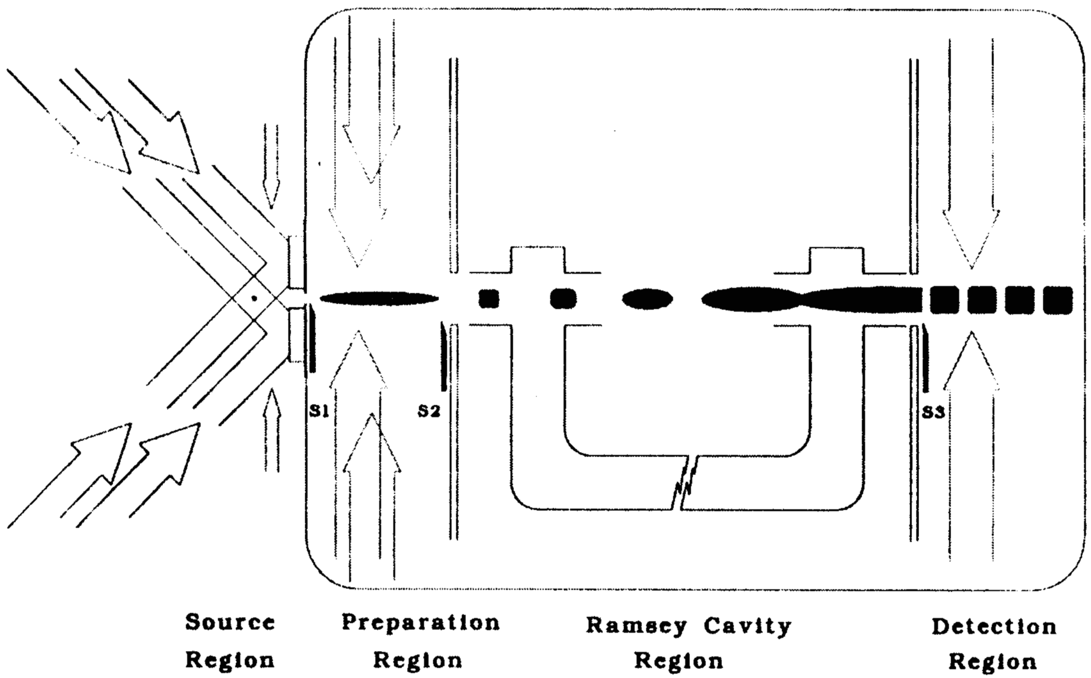
$N \propto 1/T^2$

$S/N = \sqrt{N} \propto 1/T$

$\Delta\nu = 1/2T$

$$\sigma_y(\tau) = \frac{\Delta\upsilon}{\pi\upsilon\, S/N}\sqrt{\frac{T}{\tau}} \propto \sqrt{T}$$

Laser Cooled Cesium Clock for Space



Clock Comparison

Earth-based Clocks: Space Clocks:

	NIST-7	Cs Fountain Clock	JPL Linear Ion Trap	PARCS	Ultimate Space Clock
Accuracy (realization of the second)	5×10^{-15}	1.4×10^{-15}	–	1×10^{-16}	1×10^{-17}
Stability	$4 \times 10^{-13}/\tau^{1/2}$	$1.5 \times 10^{-13}/\tau^{1/2}$	$3 \times 10^{-14}/\tau^{1/2}$	$3 \times 10^{-14}/\tau^{1/2}$	$5 \times 10^{-16}/\tau^{1/2}$

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